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Two-photon Higgs width and triple Higgs coupling in 2HDM at SM-like scenario

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ABSTRACT: Within 2HDM, sizable deviations of the triple Higgs coupling and the two-photon Higgs width from their SM values can have a common origin. If SM-like scenario for the observed Higgs boson is realized, mentioned deviations can be either visible simultaneously or not observable at the LHC.

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1 Introduction

The recent discovery of a Higgs boson with $M \approx 125$ GeV at the LHC [1]-[4] suggests that the spontaneous electroweak symmetry breaking is most probably brought up by the Higgs mechanism. The simplest realization of the Higgs mechanism introduces a single scalar isodoublet ϕ with the Higgs potential $V_H = -m^2(\phi^\dagger\phi)/2 + \lambda(\phi^\dagger\phi)^2/2$. This model is usually called “the Standard Model” (SM).

The current data do not rule out the possibility of extended Higgs models. The two-Higgs-Doublet model (2HDM) presents the simplest extension of the standard Higgs model [5]. Here the standard Higgs doublet is supplemented by an extra hypercharge-one doublet. The 2HDM offers a number of phenomenological scenarios with different physical content in different regions of the model parameter space, such as a natural mechanism for spontaneous CP violation, etc. [5]-[7]. For example, the Higgs sector of the MSSM is a particular case of 2HDM. Some variants of 2HDM have interesting cosmological consequences [8],[9].

This model contains a charged Higgs boson H^\pm with mass M_\pm and three neutral Higgs scalars h_a with masses M_a , generally with indefinite CP parity. We name the observed Higgs boson as h_1 ($M_1 = 125$ GeV). The observation of all these particles is a necessary step in the verification of the model. However, new bosons $h_{2,3}$, H^\pm may escape observation in the experiments of nearest future (see for details [10],[11] and many references therein). Nevertheless, even before this observation, there are processes that allow in principle to detect some effects beyond the SM.

(i) The detection of a triple Higgs vertex $g(h_1h_1h_1)$, which is scheduled in the LHC and other colliders, presents the necessary step in the verification of the Higgs mechanism. The main problem discussed below is – in which cases future observation of this vertex will be useful for finding New Physics effects. We note that it will be useful only if this vertex differs strongly from its SM value. We discuss cases in which it can happen provided SM-like scenario for Higgs boson (see below) is realized. One important opportunity is related to the unusual value of H^+H^-h interaction. If such value is realized, visible effect in the

two-photon width should be observed. That is why we include in the text the discussion of this width.

(ii) The loop obliged interactions of the Higgs boson ($h_1\gamma\gamma$, $h_1Z\gamma$, h_1gg) present a good opportunity to discover unusual properties of h_1 in its interactions with other particles. The value of $h_1\gamma\gamma$ interaction depends on the value of the $H^+H^-h_1$ vertex regardless of the possibility of observing H^\pm . These loop obliged couplings were calculated in many papers. However, the effects of a charged Higgs boson loop and the possible admixture of CP-odd component of the neutral Higgs boson have not been analyzed in sufficient detail until now.

2 Basics

Relative couplings.

We use relative couplings, defined as ratios of the couplings of each neutral Higgs boson h_a with the fundamental particle P to the corresponding SM couplings and dimensionless relative couplings for interactions $H^\pm W^\mp h_a$ and $H^+H^-h_a$:

$$\begin{aligned}\chi_a^P &= \frac{g_a^P}{g_{\text{SM}}^P} \quad (P = V (W, Z), q = (t, b, \dots), \ell = (\tau, \dots)); \\ \chi_a^{H^+W^-} &= \frac{g(H^+W^-h_a)}{M_W/v}, \quad \chi_a^\pm = \frac{g(H^+H^-h_a)}{2M_\pm^2/v}.\end{aligned}\tag{2.1}$$

The neutrals h_a generally have no definite CP parity. Couplings χ_a^V and χ_a^\pm are real due to Hermiticity of Lagrangian, while other couplings are generally complex. The $\text{Re}(\chi_a^f)$ and $\text{Im}(\chi_a^f)$ are responsible for the interaction of fermion f with CP-even and CP-odd parts of h_a respectively. (In particular, for the CP-conserving case with $h_3 = A$ we have $\text{Im}(\chi_{2,1}^f) = 0$, $\text{Re}(\chi_3^f) = 0$).

The relative couplings obey the following **sum rules** [12]-[14]:

$$\sum_a (\chi_a^V)^2 = 1, \quad |\chi_a^V|^2 + |\chi_a^{H^\pm W^\mp}|^2 = 1, \quad \sum_a (\chi_a^f)^2 = 1.\tag{2.2}$$

We omit the adjective "relative" further in the text.

The minimal complete set of measurable quantities.

The minimal complete set of measurable quantities (we call them "observables") determines all parameters of the most general Higgs Lagrangian. It was found in [14]. This set is subdivided naturally into two subsets. The first subset contains v.e.v. of Higgs field $v = 246$ GeV, masses of all Higgs bosons $M_{1,2,3}$, M_\pm and two out of three couplings χ_a^V . To form the second subset of complete set, one need to use triple and quartic Higgs self-interactions. The minimal simple collection of parameters of the second subset contains three triple couplings $H^+H^-h_a$ (quantities χ_a^\pm) and one quartic coupling $g(H^+H^-H^+H^-)$. The parameters of Higgs potential are expressed simply via these observables [14].

In the most general 2HDM, all these observables are independent of each other. Their possible values are only limited by general conditions, such as positivity and sum rules (2.2). In some special variants of 2HDM, additional relations between these parameters

may appear (for example, in the CP conserving case we have $\chi_3^V = 0$, $\chi_3^\pm = 0$).

SM-like scenario.

Experimental data allow to suggest that the Nature realizes SM-like scenario:

- 1) We observe a single Higgs boson. Its mass $M \approx 125$ GeV, we call it h_1 .
- 2) The Higgs boson couplings with fundamental particles P (gauge bosons V and fermions f) are close to the SM expectations within experimental accuracy (see e.g. [15]-[17]):

$$\varepsilon_P = |1 - |\chi_1^P|^2| \ll 1 \quad (P = V(W, Z), \quad f = (t, b, \tau, \dots)). \quad (2.3)$$

However, this statement remains only a plausible hypothesis until the couplings are measured with sufficient accuracy. The crucial point of forthcoming discussion is a small, but non-zero, value of ε_V , for example $\varepsilon_V \sim 0.1$. (The *decoupling limit* is realized at $\varepsilon_V \rightarrow 0$.) The W -fusion experiments are of the greatest interest here.

Some couplings in the SM-like scenario

1. Because of the first SR (2.2), the couplings of other neutrals h_a with gauge bosons χ_a^V are small (these Higgses are *gaugefobic*),

$$|\chi_a^V|^2 < \varepsilon_V \ll 1, \quad a = 2, 3. \quad (2.4)$$

2. Because of the second SR (2.2), the absolute values of non-diagonal couplings with EW gauge bosons $\chi_a^{W^\pm H^\mp}$ for $a = 2, 3$ are close to their maximal values, while similar coupling for the observed Higgs $\chi_1^{W^\pm H^\mp}$ is small¹:

$$a) \quad |\chi_a^{W^\pm H^\mp}|^2 \approx 1; \quad b) \quad |\chi_1^{W^\pm H^\mp}|^2 \sim \varepsilon_V \ll 1. \quad (2.5)$$

3 Higgs two-photon width and gluon fusion

The equations for Higgs two photon width $\Gamma(h_a \rightarrow \gamma\gamma)$ were originally derived in [25]. These widths are the sums of C-even and C-odd contributions:

$$\Gamma_a^{\gamma\gamma} = \frac{\alpha^2 M_a^3}{256\pi^3 v^2} (|\Phi_a^{E\gamma}|^2 + |\Phi_a^{O\gamma}|^2). \quad (3.1)$$

In turn, quantities $\Phi_a^{E\gamma}$ and $\Phi_a^{O\gamma}$ are the sums of the contributions $\Phi_J(r_a^P)$ of different charged particles P with mass M_P and spin J , circulating in loops (superscript E and O mark CP-even and CP-odd quark loop contributions).

$$\begin{aligned} \Phi_a^{E\gamma} &= \chi_a^V \Phi_1(r_a^W) + \sum_f \text{Re} \chi_a^f N_c Q_f^2 \Phi_{1/2}^E(r_a^f) + \chi_a^\pm \Phi_0(r_a^\pm), \\ \Phi_a^{O\gamma} &= \sum_f \text{Im} \chi_a^f N_c Q_f^2 \Phi_{1/2}^O(r_a^f); \quad r_a^P = \frac{4M_P^2}{M_a^2}. \end{aligned} \quad (3.2)$$

¹The calculations of $H^- \rightarrow W^- h_1$ decay at LHC in [18],[24] are made in the particular case of CP-conserving 2HDM and in addition to that, in the case when ε_V is not very small.

In contrast to the SM, in these equations the contribution of H^\pm (not discovered yet) is added. (At large $|\chi_a^t|$ and (or) $|\chi_a^\pm|$ one-loop equations $\Phi_{1/2}^{E,O}$ and Φ_0 must be modified.)

$$\begin{aligned}\Phi_1(r) &= 2 + 3r + 3r(2-r)\phi^2(r), & \Phi_0(r) &= r[1 - r\phi^2(r)], \\ \Phi_{1/2}^E(r) &= -2r[1 + (1-r)\phi^2(r)], & \Phi_{1/2}^O(r) &= -2r\phi^2(r).\end{aligned}\tag{3.3}$$

$$\phi(r) = \theta(r-1) \arcsin \frac{1}{\sqrt{r}} + \theta(1-r) \left(\frac{\pi}{2} \theta(r) + i \ln \left(\frac{1 + \sqrt{1-r}}{\sqrt{|r|}} \right) \right). \tag{3.4}$$

The latest data show that $\Gamma(h_1 \rightarrow \gamma\gamma)$ is close to its SM value. In assuming h_1 to be CP-even and $|\chi_1^\pm| \lesssim 1$, these observations provide a basis for the claim that $\chi_1^V \approx 1$ and $\chi_1^t \approx 1$ (SM-like scenario) [15]-[17]. This very opportunity was considered in [26]-[30] where two facts about Higgs with mass $M_1 = 100 \div 140$ GeV were established.

(i) Contribution from charged Higgs loop with $\chi_1^\pm \approx 1$ reduces $\Gamma(h_1 \rightarrow \gamma\gamma)$ by about 10% (that is within accuracy of modern data).

(ii) At $\chi_1^t \approx -1$ the width $\Gamma(h_1 \rightarrow \gamma\gamma)$ increases by factor about 2.5.

The latter fact means that the value of $\Gamma(h_a \rightarrow \gamma\gamma)$, close to SM value, can be obtained not only at $\chi_1^t \approx 1$ but also at negative χ_1^t with $|\chi_1^t| < 1$. Similar conclusions were obtained in detailed analysis of modern data in [15]-[17]. The cases of big CP-odd admixture in h_1 and sizable difference $\chi_1^\pm - 1$ are not explored in details yet. In particular, they were left out in the interpretation of data [19]-[22] – see [23].

Gluon fusion.

The cross section of gluon fusion is given by the same quark loop integrals (3.3). This cross section is saturated by t -quark loop. Therefore in the one-loop approximation this cross section is expressed via the cross section $\sigma(gg \rightarrow h_{SM}^{wb}(M_a))$ for possible SM Higgs boson with mass M_a :

$$\begin{aligned}\sigma(gg \rightarrow h_a) &= \sigma(gg \rightarrow h_{SM}^{wb}(M_a)) \left[(Re\chi_a^t)^2 + (Im\chi_a^t)^2 \Phi^{O/E}(r_a^t) \right], \\ \text{where } \Phi^{O/E}(r) &= \left(\Phi_{1/2}^O(r) / \Phi_{1/2}^E(r) \right)^2.\end{aligned}\tag{3.5}$$

For $M_a = 125$ GeV and 300 GeV we have $\Phi^{O/E} \approx 2.25$ and 2.7 respectively.

4 Triple Higgs coupling

The measuring of $g(h_1 h_1 h_1)$ is scheduled in the LHC and other colliders. The accuracy of these measurements can not be high, since in each case corresponding experiments deal with interference of two channels with identical final state – an independent production of two Higgses and production of Higgses via $h_1 h_1 h_1$ vertex (at LHC – from t -loop). This interference is mainly destructive [31]. For example, for 100 TeV hadron collider with total luminosity $3/abn$ one can hope to reach accuracy of 40% in the extraction of this vertex from future data [32].

The equation for triple Higgs coupling in terms of the introduced observables in the most general 2HDM was found in the [14]:

$$g(h_1 h_1 h_1) = \frac{M_1^2}{v} \chi_{111}; \quad \chi_{111} = \chi_1^V \left\{ 1 + (1 - (\chi_1^V)^2) \left[1 + \sum_b 2 \frac{M_b^2}{M_1^2} (\chi_b^V)^2 \right] + (1 - (\chi_1^V)^2) \frac{2M_\pm^2}{M_1^2} \left[\sum_b \chi_b^V \chi_b^\pm - 1 + \text{Re} \left(\sum_b \chi_b^{H^+ W^-} \chi_b^\pm \frac{\chi_1^{H^+ W^-}}{\chi_1^V} \right) \right] \right\}. \quad (4.1)$$

Here factor M_1^2/v is the SM result, and $\chi_{111} - 1$ represents the New Physics effect.

In the SM-like scenario it is easy to estimate

$$\chi_{111} \approx (1 - \varepsilon_V/2) \{ 1 + \varepsilon_V [3 + B\varepsilon_V + 2B_\pm (\chi_1^\pm - 1 + \varepsilon_V K_\pm)] \}, \quad (4.2)$$

$$B \sim \sum_b M_b^2/M_1^2; \quad B_\pm = 2M_\pm^2/M_1^2, \quad K_\pm \sim \chi_b^\pm, (b = 2, 3).$$

We see that at moderate values of parameters, relative coupling χ_{111} is close to 1, and it is difficult to expect sizable effect^{2,3}.

There are *special exotic values of model parameters* providing sizable deviations of triple Higgs coupling from its SM value, i.e. $|\chi(h_1 h_1 h_1) - 1| \gtrsim 1$. Our estimates are valid if ε_V is not extremely small. (In the opposite case big deviations of χ_{111} from 1 can appear in the range of parameters, violating perturbativity and giving partially strong interaction in the Higgs sector with possible new phenomena. This case should be explored separately.) For numerical estimations we use $\varepsilon_1^V \approx 0.1$.

(i) The most interesting case presents itself if the value of $B_\pm \chi_1^\pm$ product is big ($\gtrsim 1/\varepsilon_V$). The big value of vertex $H^+ H^- h_1$ (even at moderate value of charged Higgs mass) results in $|\chi(h_1 h_1 h_1) - 1| \gtrsim 1$. Simultaneously it gives big effect in $\Gamma(h_1 \rightarrow \gamma\gamma)$. Coexistence of these two phenomena can be an important source of knowledge about the charged Higgs boson before its direct discovery.

(ii) Other non-trivial opportunities for observation of sizable effect in triple Higgs coupling present themselves in less natural cases – when quantities B and (or) $B_\pm K_\pm$ are huge, $\gtrsim 1/\varepsilon_V^2$:

(ii-a) One or both of Higgs neutrals $h_{2,3}$ are heavier than a few TeV. Direct discovery of such Higgs seems to be a difficult task. Therefore for a long time detection of this phenomenon may become an important source of knowledge about these heavy neutrals.

(ii-b) The couplings $\chi_a^\pm \gtrsim 10$. In this case the two-photon width $h_a \rightarrow \gamma\gamma$ will be strongly different from similar width, calculated for the would-be SM Higgs boson with the same mass.

²For the particular CP conserving case and with moderate values of parameters such conclusion was obtained in [33], [34] (see also [35], [36] for the CP conserving MSSM). For the nMSSM (2HDM + Higgs singlet) values χ_{111} can vary from 1.9 to -1.1 [35], [36].

³For some particular variant of MSSM the value of triple Higgs coupling with radiative correction $g^{ren}(h_1 h_1 h_1)$ looks essentially different from its tree form in SM, M_1^2/v [37]. However, in this very approximation one must take into account the mass renormalization $M_1 \rightarrow M_1^{ren}$. In ref. [38] it was found that $g^{ren}(h_1 h_1 h_1) \approx (M_1^{ren})^2/v$ – similar to the SM.

5 Summary

The presented discussion can be summarized in the following points.

- The non-trivial effects can appear only in the case when ε_V is not extremely small.
- **Two photon width $\Gamma(h_1 \rightarrow \gamma\gamma)$.** Direct measuring of $h_1 WW$ and $h_1 t\bar{t}$ couplings is a very important task. Besides, the recent analysis of two photon width and gluon fusion for observed Higgs boson h_1 should be supplemented by more detailed study of effect of possible CP violation. In this respect experimental study of asymmetries in the $h_1 \rightarrow \tau\bar{\tau}$ etc. is essential (see [39] for estimates). Unfortunately, high accuracy in the determination of $h_1 H^+ H^-$ coupling will not be achieved in the nearest future, because of low accuracy in the measuring $h_1 \gamma\gamma$ vertex at LHC.
 - **Triple Higgs vertex.** At moderate values of masses, etc. the observation of sizable deviation from SM prediction in the triple Higgs vertex is unlikely. The sizable effect here may occur in more or less exotic cases.
 - (i) Strong enough $h_1 H^+ H^-$ interaction (it gives an effect in $\Gamma(h_1 \rightarrow \gamma\gamma)$).
 - (ii-a) Extremely heavy additional neutral Higgs bosons.
 - (ii-b) Strong interaction $h_a H^+ H^-$.
 - Special case appears in the SM-like scenario at $400 \text{ GeV} > M_2 > 250 \text{ GeV}$ if $|\chi_2^t| > 1$. In this case Higgs boson h_2 is relatively narrow and the cross section of gluon fusion $gg \rightarrow h_2$ can be larger than that for the would-be SM Higgs boson with mass M_2 . The process $gg \rightarrow h_2 \rightarrow h_1 h_1$ can be seen as a resonant production of $h_1 h_1$ pair. In principle, it allows to discover the mentioned h_2 at LHC (see example in [34], [40], [41] for special sets of parameters).

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